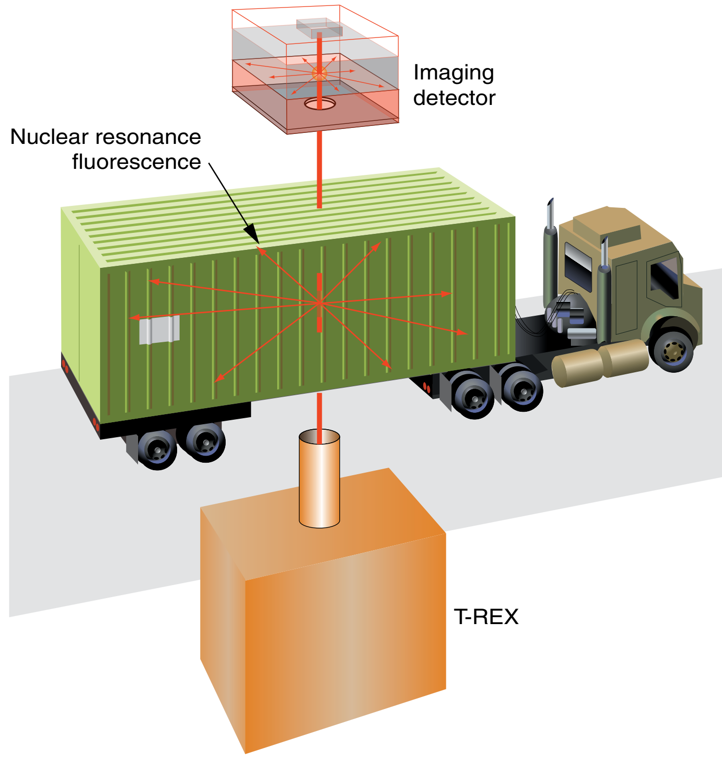
Taking a Gander with Gamma Rays

SINCE their discovery in 1895, x rays have been used in countless applications to make the unseen visible—bones beneath skin and tissue, metal beneath plastic. These electromagnetic waves can penetrate low-density materials (such as skin and plastic), but higher density materials (bone and metal) significantly scatter or absorb photons. Recording the photons that pass through only some materials creates the distinctive "shadow picture" of an x-ray image, which shows a feature previously hidden from view. In special cases, scientists can use x-ray imaging to determine the atomic composition of matter—that is, its constituent elements. Determining the isotopic variety of observed elements would also be useful for some applications, for example, to distinguish depleted uranium from weapons-grade uranium. However, developing those capabilities requires a radiographic source that uses the next higher energy range in the electromagnetic spectrum.

Christopher Barty, a physicist in Livermore's National Ignition Facility Programs Directorate, has brought together Laboratory experts in lasers, optics, accelerators, and nuclear physics to design such a source. Called T-REX, the Thomson-radiated extreme x-ray system will produce photons at extremely high energies with the brightness, or photon spectral, spatial, and temporal density, needed to study isotopes. This capability will allow researchers to address challenges in fields such as nonproliferation, homeland and international security, and waste identification.



Livermore researchers are developing a system that combines the capabilities of a Thomson-radiated extreme x-ray (T-REX) system with a nuclear resonance fluorescence technique to detect small amounts of nuclear materials and image their isotopic distribution. The system could be used to inspect well-shielded objects, such as cargo containers moving through a terminal.

From X to Gamma Rays

T-REX builds on a past Livermore project called Picosecond Laser–Electron Interaction for the Dynamic Evaluation of Structures (PLEIADES), which was funded by the Laboratory Directed Research and Development (LDRD) Program. The goal of PLEIADES was to develop a system for generating high-energy x rays to study the dynamic processes in biological and energetic materials. The project team used a 100-megaelectronvolt (MeV) accelerator to create a beam of energetic electrons that were then smashed into photons generated from an ultrashort-pulse, 10-terawatt laser. (See *S&TR*, October 2001, pp. 13–15.) The collision of electrons and photons produces pencillike beams of x rays by the so-called Thomson-scattering process. With the PLEIADES system, the energy of the Thomson x rays can be adjusted, or tuned, by changing the electron bunch energy or the laser photon energy, resulting in picosecond-long pulses of bright, tunable x rays between 10 and 100 kiloelectronvolts (keV).

"Photons in this range can excite or ionize even the most tightly bound atomic electrons," says Barty. "We could use these photons to probe the atomic-scale dynamics of various physical, chemical, and biological phenomena and to develop element-specific tools for radiography and radiology." In 2003, the PLEIADES system generated record pulses of 70-keV x rays.

That success led Barty and Livermore physicist Fred Hartemann to consider using the Thomson-scattering process to create photons with energies above 100 keV. Their calculations indicated that a beam's brightness could be increased rapidly by using more energetic electrons and by reducing the interaction region between the laser and electrons.

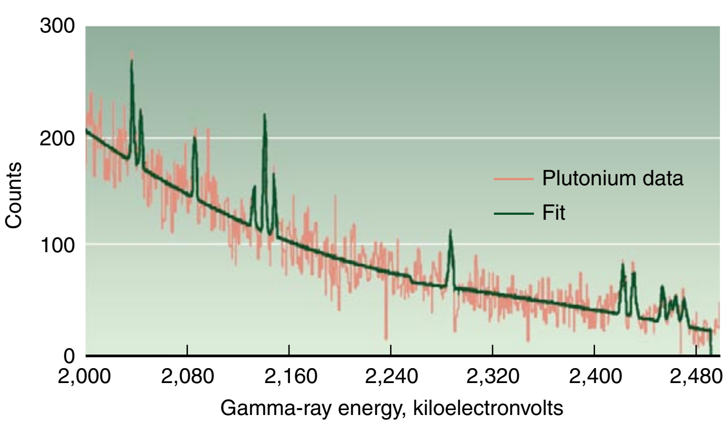
"The number of photons generated from the Thomson-scattering process increases as a square of the electron energy," says Barty. "We calculated that, by using relativistic electrons and energetic photons from a laser, we could generate a tunable, nearly single color, bright beam of photons between 100 keV and several megaelectronvolts."

Traditionally, beams in this particular energy regime are created in synchrotron facilities. The problem with synchrotron-generated radiation is that the brightness of the generated beam declines rapidly as a function of photon energy, and the photons produced span a wide, continuous spectral range. Thomson scattering would alleviate this problem if the technical issues in building a system could be resolved. According to Barty, conservative estimates indicate that, at 1 MeV, a system using Thomson scattering could generate a beam of photons with a spectral, spatial, and temporal density a quadrillion (10^{15}) times greater than that from the Advanced Photon Source at Argonne National Laboratory, which is the brightest synchrotron machine in the Department of Energy's (DOE's) complex.

Detecting Concealed Nuclear Materials

Barty and Hartemann are working with Dennis McNabb, Jason Pruet, and others on an LDRD project to develop a 15- by 3-meter T-REX system capable of producing tunable pulses of 700-keV photons. "We visualize applications in radiography, spectroscopy, imaging of special nuclear material, microcrack failure analysis, and more," says Barty. The team expects such systems to provide new research opportunities in much the same way that tunable lasers revolutionized atomic spectroscopy.

Bright gamma-ray pulses tuned to specific nuclear energy levels could be used to detect specific nuclei and isotopes, through a process called nuclear resonance fluorescence (NRF). Most nuclei have a set of nuclear "fingerprints"—several photon-excited states unique to that type. When a photon with the defined energy hits a targeted nucleus, the photon is absorbed. The excited nucleus then decays, radiating photons of the characteristic energy in all directions. The emitted energy spectrum thus identifies the nuclear species or isotope of the target.



These nuclear resonance transitions for plutonium-239 occur at energy levels that can be reached by a T-REX gamma-ray source.

Maurice Goldhaber and Edward Teller described the basic physics of NRF in 1948. In 2003, William Bertozzi from the Massachusetts Institute of Technology proposed using the technique to detect nuclear materials, such as highly enriched uranium, in shipping containers and trucks. At that time, however, no available system could generate tunable gamma-ray beams for this application. Barty's team wants to combine fully developed T-REX capabilities with the NRF technique to detect the presence of specific isotopes and image their distribution.

The Department of Homeland Security's Domestic Nuclear Detection Office is funding research to explore this imaging and detection capability. The proposed system, called fluorescence imaging in the nuclear domain with extreme radiation (FINDER), could be used to image the isotopic composition of materials inside well-shielded objects, such as cargo containers moving through an inspection terminal. If successful, a FINDER system based on T-REX technology could provide a solution to the challenge of detecting concealed highly enriched uranium.

Calculations by Pruet and others indicate that the technology has tremendous potential for verifying the contents of cargo containers without interrupting the flow of commercial traffic. In addition, this isotopic imaging method, which the team calls isotope photography, could be used in stockpile surveillance and as a safer method for evaluating legacy nuclear waste streams. "We're also exploring ways to apply T-REX technology to important DOE science missions, such as next-generation light sources and high-intensity megaelectronvolt photon beams for fundamental nuclear science measurements," says Barty.

The Future Looks Bright

The T-REX team is designing and constructing the gamma-ray source that will be used to demonstrate the FINDER concept. In addition, researchers at Lawrence Livermore and Pacific Northwest national laboratories and Passport Systems, Inc., in Acton, Massachusetts, have identified NRF transitions in uranium-235 and plutonium-239 at energy levels that can be reached by a 2-MeV-class T-REX source. Says Barty, "Completing this research will place the Laboratory in a leading position with respect to gamma-ray source capability and the development of novel applications in nuclear photo science."

—Ann Parker

Key Words: cargo inspection, gamma-ray spectrum, isotope photography, nuclear resonance fluorescence (NRF) imaging, Thomson-radiated extreme x-ray (T-REX) system, Thomson scattering.

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